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Prepared by:

Columbia Astrophysics Laboratory
Departments of Astronomy and Physics
Columbia University
538 West 120th Street
New York, New York 10027

Submitted by:

The Trustees of Columbia University
in the City of New York
Box 20, Low Memorial Library
New York, NY 10027

Title of Research: **"Nonthermal Processes around Collapsed Objects: High Energy Gamma Ray Sources in the Radio Sky"**

Principal Investigator:

David J. Helfand
Professor of Astronomy, Columbia University

Co-Investigators:

Malvin Ruderman
James H. Applegate
Robert H. Becker

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Nonthermal Processes around Collapsed Objects: High Energy Gamma Ray Sources in the Radio Sky

I. Introduction

In our proposal responding to the initial Guest Observer NRA for the Compton Gamma Ray Observatory, "Nonthermal Processes Around Collapsed Objects: High Energy Gamma Ray Sources in the Radio Sky", we stated that "At high energies...the identity of the principal Galactic source population remains unknown" although the "one certain source of high energy emission is young radio pulsars". These two statements remain true, although at this writing, eighteen months after the beginning of the Compton all-sky survey, much of the gamma-ray data required to greatly extend our knowledge of the Galaxy's high energy emission has been collected. The thrust of the program supported by our grant was to collect and analyze a complementary set of data on the Milky Way at radio wavelengths in order to help identify the dominant Pop I component of the Galaxy's gamma ray sources, and to pursue theoretical investigations on the origins and emission mechanisms of young pulsars, the one component of this population identified to date.

We summarize here our accomplishments under the grant. In Section II, we decribe our VLA surveys of the Galactic Plane along with the current status of the radio source catalogs derived therefrom; unfortunately, owing to the TDRSS antenna problem and subsequent extension of the Sky Survey, we were not able to carry out a comparison with the EGRET data directly, although everything is now in place to do so as soon as it becomes available. In Section III, we summarize our progress on the theoretical side, including the substantial completion of a dissertation on pulsar origins and work on the high energy emission mechanisms of isolated pulsars. We list the personnel supported by the grant in section IV and provide a complete bibliography of publications supported in whole or in part by the grant in the final section.

II. The radio surveys

Since the first survey of the Galactic plane for sources of gamma rays at energies greater than 100 MeV, roughly two dozen discrete emitters have been catalogued, but only three have been identified at other wavelengths: the Crab, Vela, and, recently, Geminga. All three are rotation-powered neutron stars, all three are extreme Pop I objects, close

to the plane of the Milky Way, and the first two are radio emitters as well (Geminga may also emit radio waves, but apparently not in our direction). These are the types of sources our radio surveys of the Galaxy were meant to pinpont as a means of identifying the even larger number of high energy gamma-ray sources anticipated from the EGRET plane survey. In our original, two-year proposal, our goal was to complete a multifrequency survey of the Galactic plane at 6, 20, and 90 cm using the VLA and to prepare catalogs of sources for comparison with the EGRET maps as a step toward identification of the large population of gamma-ray point sources expected to be discovered. While the stretchout of the Compton Sky Survey occassioned by the TDRSS antenna failure prevented us from having access to a catalog of EGRET sources in the limited time during which the grant was in effect, we have largely completed the task of preparing radio catalogs and placing them in the public domain so that such comparisons can proceed as soon as the EGRET catalog is available. We briefly outline the major accomplishments of the surveys below:

- publication of a complete catalog of radio sources at 20cm with angular diameters $\lesssim 20''$ in the longitude range from $-20° \leq \ell \leq +120°$ with $|b| \lesssim 0.8°$ above a flux density threshold of $\sim 10 - 20$ mJy. This catalog of 1992 discrete sources was derived from the analysis of 843 10^6 pixel images constructed from VLA snapshots. The source positions are accurate to $\lesssim 3''$. A detailed comparison with other radio, optical, and X-ray surveys of the plane provides annotations for all sources detected previously. The number of new very compact (and presumable very young) supernova remnants discovered is very small (or nonexistant), but the number of extreme Pop I sources found exceeds 300 and their scale height of only ~ 25 pc is the smallest yet found for any population of objects; they clearly mark the birthplaces of pulsars, good EGRET source candidates.

- publication of an extension of the survey at 20cm in the inner part of the Galaxy between longitudes $-10°$ and $+40°$ up to latitudes of $\pm 1.8°$. Analysis of a total of 404 2×10^6 pixels images yielded 1457 new radio sources, bringing the total in this longitude range within 1.8° of the plane to 2135. A sophisticated matching algorithm was developed to compare this catalog with the IRAS PSC and 269 high-probability matches were found. Examination of the IRAS colors for these objects allows preliminary classification as compact and ultracompact HII regions, planetary nebulae, evolved stars, and extragalactic objects. The former two source types dominate, although the lack of detection in some of the IRAS bands does not always distinguish clearly between them (see below). Nonetheless, a complete, flux limited sample of over 150 compact HII regions and nearly 100 PNe candidates have been identified.

- completion of a 6cm survey of the inner portion of the Galaxy accessible to the VLA ($-10° \leq \ell \leq +40°$) within $\pm 0.4°$ of the plane. This considerable undertaking required observation of over 1500 fields and the construction of 10^6 pixel images from each, followed by extraction of sources down to a flux density limit of 2.5 mJy. A total of 1272 objects were found (~ 30 deg^{-2}), only ~ 400 of which were detected in the 20cm survey. Comparison with the IRAS PSC and other catalogs as well as an examination of the sources' latitude distribution and radio spectral index information produces a list of over 500 compact HII regions, the most comprehensive delineation of these tracers of massive star formation ever compiled. In addition, the derivation of spectral indices for all sources in both catalogs by matching counterparts, or, more frequently, extracting upper limits from the original maps at the frequency at which a source was undetected, allowed us to produce a list of potential pulsar candidates with steep ($\alpha < -1.8$) spectral indices. As outlined in the proposal, there are a number of reasons that young radio pulsars might be missed in standard pulsar searches — short periods, large amounts of multipath scattering, large duty cycles, pole-on orientations, smothering by a binary companion wind, and misdirected beams (which nevertheless light up synchrotron nebulae) — and these steep spectrum radio sources near the plane could represent examples of such phenomena; they would certainly be excellent candidates for followup observations should an EGRET error circle contain one.

- mapping of 15 degrees of the Galactic plane out to latitudes of ± 3.5 degrees at 90 cm with the VLA. While the ultimate signal-to-noise has yet to be reached in creating images of these data, they will ultimately provide a survey that is a factor of 30 better in both angular resolution and sensitivity than any previous effort. Initial maps of the entire region have been produced, and show a large number of previously uncatalogued extended sources which are candidates for new supernova remnants, potential sites for gamma-ray emitting pulsars.

- the application of narrow-band near-infrared imaging in the [SIII] lines in order to distinguish radio-selected planetary nebulae from HII regions or other source types. PNe are not expected to be high energy gamma-ray sources, while compact HII regions should mark the sites of the birth of such objects. Our efforts to distinguish the radio/IRAS-selected samples of these objects is therefore important to defining clean samples for statistical correlation with the EGRET source catalog. To date, over 50 objects (including some young supernova remnant candidates from the 20cm and 90cm catalogs) have been observed and an analysis of the first half of these data has been submitted for publication.

Our delineation of the extreme Pop I sources in the Galaxy may well turn out to be relevant to Compton Observatory results other than the EGRET point-source catalog. For example, the recent maximum entropy map of the ^{26}Al line produced by the COMPTEL group shows a local *minimum* between 25 and 35 degrees longitude, whereas our longitude distributions of compact HII regions, the ideal Pop I tracer shows a global *maximum* at this location. If the preliminary COMPTEL results stand, this anticorrelation would argue strongly against a majority of the ^{26}Al arising from Type II supernovae.

Both the 20cm and 6cm catalogs are being installed in the NED database and are available on request in electronic form. A nine-track tape archive of the original VLA images is also being maintained. We hope to continue work in the future on the 90cm data, and, as soon as the EGRET plane survey catalog is available, will undertake a comparison with the radio images of the Galaxy we have constructed.

III. Theoretical work

The standard theoretical picture of the origin of runaway OB stars predicts that the majority of them have young neutron star companions. These neutron stars have been looked for at X-ray wavelengths (accretion from the massive star wind) and at optical wavelengths (Doppler shifts due to the orbital motion of the massive star), but they have never been seen. These neutron stars should be young enough to be active pulsars. The radio pulses do not escape the wind of the massive star, but gamma rays do. Thus, we proposed to study the gamma ray emission from OB runaways. Our major results are summarized below:

1) We have compiled a catalog of runaway OB stars to compare with the point source catalog to be produced by the EGRET team.
2) We have developed a Monte-Carlo model for the evolution of massive binaries through the explosion of the primary in order to calculate the orbits for the neutron star companions of the OB runaways. This step is essential because the consequences of the collision between the massive star wind and the pulsar wind are quite sensitive to the semi-major axis and eccentricity of the orbit of the neutron star, and the orbit is constrained by the mass and velocity of the runaway star, the limit on the orbital motion of the OB star, and the limit on the X-ray emission from the system.

Geminga's observed γ-ray emission was shown to be consistent with outer-magnetosphere accelerator models for rapidly spinning pulsars with highly inclined dipoles. Such pulsars could be exceptionally efficient in converting much of their total spin-down power to pulsed γ-ray emission. (If aligned, however, pulsars with the same spin and dipole

strength might be unable to sustain such strong γ-ray emission.) They would also give the observed double-pulsed profile with a nearly 0.5 phase separation. Geminga would then be a γ-ray pulsar with the same kind of accelerator and γ-ray emission mechanisms as the more rapidly spinning Crab, Vela, PSR 1706-44 and (probably) PSR 0540-69. Differences between it and its siblings would come from the large inclination angle of its dipole which allows its outer-magnetosphere accelerator to be closer to the star where its local magnetic field, current flow, and power can be similar to that of the Vela pulsar.

Such a Geminga model predicts a beaming of energetic γ-rays close enough to the star to give copious $e^{\pm}$ production in the stellar magnetic field and a large circumstellar pair density from pair inflow toward the stellar surface. These pairs may quench the canonical polar cap accelerators which would otherwise give rise to radio emission. Energetic particles would flow inward from the magnetospheric accelerator responsible for Geminga's γ-rays, and heat the star's polar cap. The resulting polar cap X-ray emission would be reflected back to the stellar surface by cyclotron resonance scattering on the very copious circumstellar pairs. The keV X-ray emission from the hot polar cap would then ultimately escape mainly as much softer (10^{-1}keV) X-rays from the much larger total surface area of the star. The expected X-ray emission features appear to resemble those observed.

IV. Personnel supported by the grant

The following faculty investigators and their students were supported under this grant to pursue the research described above.

David J. Helfand, PI (Professor of Astronomy, Columbia University) Received 2 months of salary support for direction of the project and participation in the radio sky surveys

James H. Applegate, Co-I (Associate Professor of Astronomy, Columbia University) Received 2 months of salary support for work on the origins of pulsars

Malvin Ruderman, Co-I (Professor of Physics, Columbia University) Received only administrative and clerical support paid for by the grant

Robert H. Becker, Co-I (Professor of Physics, University of California, Davis) Received only travel and publication cost support under this grant

James Terman (Graduate student in Physics, Columbia University) Received 16 months of salary support under the grant while working on his dissertation concerning the origin of pulsars and their velocities described in the original proposal. Will receive PhD. in the spring of 1993.

Kevin Y. Sanbonmatsu (Undergraduate Astrophysics Major, Columbia University) Worked part time during the school year on the Galactic Plane radio surveys and completed a senior thesis on radio observations of a supernova remnant which contains a high energy compact source. Graduated in 1992 and is now a graduate student in astrophysics at the University of Colorado.

Jennifer Broekman (Undergraduate Astrohysics Major, Rabi Scholar, Columbia University) Received 4 months of summer salary for work on both the 20 cm and 6 cm Galactic plane surveys. Is currently a senior, and is applying to graduate schools in Astrophysics.

IV. Publications

The following articles describing the results of the research program outlined above were published or submitted for publication in refereed journals during the eighteen-month term of the grant:

"The Infrared Properties of Compact Galactic Radio Sources," by R.L. White, R.H. Becker, and D.J. Helfand 1991, *Ap.J.*, **371**, 148.

"Compact Radio Sources Near the Galactic Plane," by D.J. Helfand, S. Zoonematkermani, R.H. Becker, and R.L. White 1991, *Ap.J. (Suppl.)*, **80**, 211.

"A Distance Determination for the Supernova Remnant G27.4+0.0 and Its Central X-ray Source," by K.Y. Sanbonmatsu and D. J. Helfand 1992, *A.J.*, **104**, 2189.

"A 5 GHz Survey of the Galactic Plane," by R.H. Becker, D. J. Helfand, R.L. White, and S. Zoonematkermani 1992, *Ap.J. (Suppl.)*, submitted.

"Observations of [SIII] Emission from Galactic Radio Sources," by V.Kistiakowski and D.J. Helfand 1992, *A.J.* (in press).

"On the Kinematics and Binary Frequency of Runaway OB Stars," by J.L. Terman and J.H. Applegate, to be submitted to *Ap.J.*

"A Model for the Origin of Pulsar Velocities," by J.L. Terman and J.H. Applegate, to be submitted to *Ap.J.*

"Gamma-ray Pulsars and Geminga," by M. Ruderman, K. Chen, K.S. Cheng and J. Halpern, to appear in *Proc. of the Third Compton Observatory Workshop* (St. Louis, Oct. 1992), N. Gehrels, ed. (in press).

"Soft X-ray Properties of the Geminga Pulsar," by J. Halpern and M. Ruderman 1992, submitted to *Ap.J.*.

"Pulsar Death Lines and Death Valley," K. Chen and M. Ruderman 1993, to appear in *Ap.J.*

The following abstracts were published and talks presented at various national and international meetings describing the results of the research program outlined above:

"Compact Sources Near the Galactic Plane," by S. Zoonematkermani, D.J. Helfand, R.H. Becker and R.L. White 1991, *B.A.A.S.*, **23**, 895.

"A 6cm Survey of the Milky Way," by D.J. Helfand, S. Zoonematkermani, R.H. Becker, and R.L. White 1991, *B.A.A.S.*, **23**, 895.